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First Annual Report

# A Fundamental and Feasibility Study of Ring-Vortex Gaseous-Core Cavity Reactor

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## I. INTRODUCTION

This is the second semi-annual progress report (from August 1, 1964 to January 31, 1965) or the first annual report from February 1, 1964 to January 31, 1965) on the Fundamental and Feasibility Study of Ring-Vortex Gaseous-Core Cavity Reactor, under the Grant No. NsG 586. Reference should be made to the statements in the first semi-annual progress report to which the present report is a continuation.

The experimental work is summarized in Part II. A number of interesting features are found. The theoretical work is outlined in Part III.

The estimate of the second year budget is enclosed in Part IV.

Three reports which are partially supported by the Grant are enclosed.

## II. EXPERIMENTS

1. Early results of the two phase vortex flow experiments on confinement of heavier fluid in a lighter driving fluid which is both injected and ejected tangentially near the outer wall of the circular chamber in the same direction based on:

Three conditions:

(a) $\frac{\rho_2}{\rho_1} > 1$ but $\frac{\rho_2 - \rho_1}{\rho_1} << 1$.

(b) Rotational velocity is low (few feet per second).

(c) Both fluids are in liquid state, the heavier fluid being admitted later to the center of the core.

Briefly, the heavier fluid can be driven to rotate and stay in the center core for a long time without much diffusion and loss. This observed fact leads us to the conclusion given in the first semi-annual report. This is the first stage of the experiments.

2. In the second stage of the two phase flow experiments, both with liquid and gas, the density increment ratio $\rho_2 - \rho_1 / \rho_1 > 1$ and the injecting fluid velocity is high (water with the velocity of 20-30 feet per second and gas with the velocity of a few hundred feet per second), the phenomen is completely different from that described in the first semi-annual report. On account of the centrifugal force, the heavier fluid which originally filled the center, drifts out and eventually rotates in the zone near the outer circular wall with the faster lighter fluid. Thus, in the zone of the center core, only the light fluid rotates there.

(a) Axial Exit.

Any axial suction from the ends will take only the light fluid. None of the heavy fluid can leak out except on occasions of start and stop when the centrifugal force does not play a role and the heavier fluid diffuses into the central core and losses to a certain extent will occur. The higher the rotation speed, the better the confinement of the heavier fluid.

(b) Outer Wall Sunction in the Tangential Direction of Rotation.

If the suction outlet is in the tangential direction of flow rotation, the lighter fluid will accelerate under suction and drift with it the heavier fluid which rotates near the outer wall. Thus the heavier fluid cannot be confined and consequently is lost. This regime of high speed is controlled by the centrifugal force and is contrary to the observed phenomena of low speed and $\rho_2 - \rho_1 / \rho_1 << 1$. Therefore, this regime is impossible to confine the heavier fluid in high speed and in high values of $\rho_2 - \rho_1 / \rho_1 > 1$.

(c) Outer Wall Suction Opposed to the Direction of Rotation.

During the experiments, it is discovered that good confinement of heavier fluid can be obtained by means of outer wall suction in the direction opposite to the direction of rotation. If the heavy fluid rotates at very high speed that higher momentum and inertia of the heavier fluid can resist the transverse motion, and the time interval for fluid passing through the suction opening is so short that the small change in transverse velocity of heavy fluid prevents itself from turning 180° angle and being sucked out of the exit. On the other hand, the lighter fluid has smaller momentum $(M_1 << M_2)$ if $\rho_1/\rho_2 << 1$, and can be decelerated very much and stopped during the short time interval of a strong suction and consequently turns 180° and flows out at the exit. This discovery is very important and leads to a good promise of the feasibility of vortex ring cavity reactor. At present, some design of a vortex ring cavity reactor is being studied. The first one will be made of glass.

## EXPERIMENTAL STUDY

The original concept of obtaining a vortex ring encased inside a cavity of toroidal-shaped walls was found to be infeasible when dealing with fluid mixtures of high density difference and high flow rate condition. Confinement of heavier fluid in the core of another lighter fluid could be realized only in the case of two fluids with low fluid density difference and under low speed and low turbulence conditions. When a vortex flow of a mixture of two fluids with wide difference of densities, a stable condition could be reached only under high vortex flow velocities. However, the core will be formed by the much lighter fluid and the heavier fluid will form a dense ring or band circling along the sidewall encasing the lighter fluid

in the center. This is contrary to all prevalent concepts of gaseous core nuclear reactors using vortex flow to confine heavy nuclear fuel in the center of the vortex. field. Accepting this observed fact of reality, further experiments were pursued to harness the observed phenomenon. Discoveries were made with astounding results that a stable ring of heavy fluid or particles could actually be formed and suspended inside a newly developed cavity model and could be completely surrounded by the much lighter propellant fluid swirling at a high discharge flow rate without carrying the heavier particle away with it. This seems to fulfill the objective of achieving vortex confinement of heavy nuclear fuel inside the gaseous nuclear reactor. Experiments were conducted using water as the propellant fluid, iron or sand particles as heavy uranium particle. Due consideration was given to the role of diffusion effect when working with gases. Experiment was also performed using Freon gas $C\,Cl_2F_2$ (molecular weight 120) as the heavy nuclear fuel, and helium (molecular weight 4) as the light propellant gas. Result of experiment showed that by a proper design of the cavity chamber using reverse flow method and sufficient vortex strength the heavy gas forms a ring rotating with the main vortex field along the side wall of the cavity while the light gas diffuses continuously through this barrier of heavy gas toward the nozzle outlet without carrying away the heavy gas with it. Within this flow field the heavy gas is indefinitely trapped inside the cavity. This shows that diffusion effect of gases will not upset the flow confinement. This also ensures the fact that the study we made with water and heavy particles, which is much easier to study and yields much more information, will also work in the case of gas mixtures.

The experimental result obtained so far is more than encouraging. Improvement of model design is required to keep the heavy particles further away from the side wall. The study at present is limited to visual observations only. Quantitative measurement of the flow field is required to analyze the flow stability and behavior. Further research with gas mixtures is required to substantiate the result. Later on, thermal effect may be introduced to obtain more realistic data for a closer approximation to the actual gaseous core reactor operation.

## DESCRIPTION OF EXPERIMENTS

a) Initial study: As reported in the first semi-annual progress report submitted in June 1964, the first two-dimensional models using water as the propellant fluid, milk or water-soluble dyes as fuel, injected into the vortex core. Dense fuel core can be formed and maintained for a long period and the propellant to fuel discharge columatric ratio is high. The result seemed quite encouraging at first. Later on, as heavier particles such as iron powder used with water or a gaseous combination of helium and bromine, confinement of heavy particles or fluids in the vortex core is no longer possible. The heavy particles, or bromine in the case of gaseous combination, tend to settle down in the bottom of the chamber. If sufficient propellant jet velocity is used it stirs up the heavy fluid or particle and drifts out through the exit passage together. Confinement of heavy fluid in the vortex core is no longer possible.

b) Second phase of work: Many configurations of cavity internal annular passage design were tried without success, when high density ratio fluid mixtures were used. However, they all tend to point to the same fact that heavy particles could not be suspended in the vortex core but would rather go to side-walls under centrifugal force effect except those near end walls which are retarded by boundary layer effect.

Through a design change of cavity annular passage using 180° reversed exit, iron particles driven by the high velocity tangential water jets will circulate along the vortex chamber wall and become completely trapped inside the cavity without drifting out to the exhaust. Using similar design principle Freon-12 gas could be trapped inside a cylindrical shape vortex chamber without being carried away by a continuous flow of helium gas under highly turbulent and high vortex speed conditions. The cavity model is cylindrical in shape, six inches in diameter and six inches long. Tangential jet speed of helium gas is about 400 ft/sec. The Reynolds number based on the tangential velocity is about 9,000. A high sensitivity Schlieren System was used to view the flow field and the trapping of freon gas, a freon gas detector was used in the nozzle exhaust to detect the loss of freon during operation. A gas chromotograph is ordered for analyzing quantitatively the volumetric flow ratio between freon and helium gas. For a first estimation, of helium to freon, the ratio is believed to be well above 100.

c) Third phase of work: While working with the cylindrical vortex chamber, discovery was made that through proper location of jets the ring of heavy particles simulating nuclear fuel could be controlled to suspend at any level of the cylindrical vortex chamber away from end walls. By admitting fluid uniformly from side walls, this ring of heavy particles could be suspended completely in the flow field without touching any part of the cavity walls. The lighter propellant fluid will diffuse through this barrier of heavy particles spiralling toward the center vortex core and exhaust through the bottom nozzle without carrying any heavy particle away with it. Stability of this rotating ring of concentrated heavy particles depends on the jet strength, direction, velocity and pressure distribution of the flow field, as well as the particle size. The relation between all these variables will have to be determined quantitatively. With this type of flow field the molecules of the light propellant gas diffuse through those of heavy fuel gas, so that all three modes of heat exchange: conduction, convection, and radiation will be of the same order of magnitude. Maximum energy transfer to exhaust propellant will be thus achieved, resulting in a much higher operating efficiency.

## III. THEORETICAL STUDY

(a) A study and analysis of the mixing of two parallel streams of different densities and temperatures are important and fundamental to the problem of fluid motion inside a cavity reactor which contains hydrogen and nuclear fuel of different temperatures and densities. A parallel magnetic field was introduced so that the fluid motion could be stabilized. This is a preparatory step to study the instability of the flow. In a more realistic case, the flow in the cavity reactor is practically in circular motion. A circular magnetic field was introduced to stabilize this swirling motion.

In the study, "Magnetohydrodynamic boundary layer between parallel streams of different magnetic fields and temperatures", by H. P. Pao and C. C. Chang (NASA Grant NsG-586, Dec. 1964), an analysis and calculations of the free laminar boundary layer flow between parallel streams of different magnetic fields and temperatures were made for an incompressible, viscous, thermally and electrically conducting fluid. Small perturbation and approximate solutions were given. The approximate solution for $\gamma = 1$ gives quite a satisfactory flow field which only involves a discrepancy of 1 per cent from the exact numerical solution in most cases. The integration of the exact boundary layer equations was carried out and some sample calculations of the velocity, magnetic and temperature fields were shown in the graphs. It is found that no steady state solution exists when the Alfven speed is greater than the fluid speed. The thickness of the flow boundary layer increases as the strength of magnetic field increases. In other words, the magnetic field has a diffusing effect upon the flow field. The thickening of the flow boundary layer reduces the velocity shear, thus, provides a stabilizing effect upon fluid motion. The possibility of an extension to the parallel streams of two different fluids is also investigated. It is seen that this extension may be readily carried out in a quite similar manner. It is hoped that a subsequent report will present an analysis of this two-fluid model. A detailed calculation on the stability of this type of flow will also be presented.

(b) In "The stability of swirling flow of a viscous conducting fluid in the presence of a circular magnetic field", by H. P. Pao, partly supported by NASA Grant NsG 586, (in preparation), a sufficient condition for the stability of swirling flow of a viscous conducting fluid in a circular magnetic field is established.

Detailed calculations for small space between cylinders are carried out. It is hoped that a subsequent report will present an analysis of the case of over-stability and the case of large spacing between cylinders.

(c) "Flow Instability of Two Layers of Viscous Fluid" - The stability of flow down an inclined plane is investigated for the case of a stratified fluid system consisting of two layers of viscous fluids of different densities. This problem is an extension of the works of Benjamin and Yih for a homogeneous fluid; thus their results are a special case of the solution for this more general problem. Asymptotic cases for long and short wave length disturbances are considered, and the neutral curve is estimated. Reynolds numbers for the bifurcation point of the neutral curve are found for various ratios of density and depth of the two layers. For long waves, shear wave instability is also studied and is found to be damped. For the purpose of comparing the relative stability between different configurations, a stability index is defined. It is found that the two-layer flow is more stable or unstable than the homogeneous case of equal total depth, depending on whether the upper fluid is lighter or heavier than the lower one. The source of instability is to be found in the presence of the interface. It is hoped that this work will bear on problems of flow stabilizing techniques and liquid extraction processes. The above work is partially supported by the Grant and report written by Dr. Kao is enclosed for review.

(d) Concentration Profile of Two-Fluid Single Phase Model - Work on the establishment of concentration profile of a two fluid single phase model in a strong gravitational field is also in progress. A perturbation procedure is used to obtain the solution.

(e) Stability of Variable Shear Flow in an Unstably Stratified Non-Viscous Medium - In the gaseous core cavity reactor, the flow is in a medium with variable shear and variable stratification. The stability question is of great interest to the feasibility of the reactor system. Unfortunately, the velocity profile and density profile are not known in any one of the experimental system studies and it is difficult to study the stability of some specific case. It seems reasonable to study the instability of a simple profile and density gradient as a first step. Dr. Eisler has been studying the problem of the stability of a shear flow in an unstable layer in the atmosphere for some time before joining the faculty of this Department. Since his work is important and does show a better understanding of the stability problem of the cavity reactor, the final phase of his paper is recommended for submission as a report to this project.

A study of the stability of a flow with variable shear in an unstably stratified density layer has been made for the case of a piecewise linear profile of the half jet type. The width of the velocity profile coincides with the width of the convective layer. In this model, a critical Richardson number is found below which instability is of the shear type and above which instability is of the convective type. No modes are found which represent an interaction of these two types. Further work is in progress for the case in which the width of the convective layer is greater than the width of the velocity profile.

Technical Reports Enclosed with the First Annual Report

65-001 "Stability of Two-Layer Viscous Stratified Flow Down an Incline Plane". by Timothy W. Kao.

65-002 "Magnetohydrodynamic Boundary Layer Between Parallel Streams of Different Magnetic Fields and Temperatures". by H. P. Pao and C. C. Chang.

65-003 "Stability of a Shear Flow in an Unstable Layer". by T. J. Eisler